FDTD Seismic Simulation of a Moving Tracked Vehicle

Stephen A. Ketcham*, Mark L. Moran*, James Lacombe*, Roy J. Greenfield+

*USACE Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL), 72 Lyme Rd, Hanover, NH 03755

+Department of Geosciences, Penn State University, University Park, PA 16802

Abstract

This paper describes the utility of a large finite-difference time domain (FDTD) simulation of seismic wave propagation from spatially and time varying sources that represent moving tracked vehicles. The focus is the computational approach and requirements for the long-duration simulation, the geologic model, the moving vehicle force algorithm, the resulting particle velocity wave fields, and example applications of the data.

The 8th order FDTD simulation consisted of parallel computations based upon a domain decomposition strategy. The computations were performed using a Cray T3E at the Army High Performance Computing Research Center. This was necessary because of the spatial extent of the model and the durations of the simulated events; the model dimension is roughly 200 m by 300 m by 80 m (deep) with 1.6-m node spacing, and the event durations were as long as 24 s with time steps of 180 μs. This duration reflects the time required for the vehicle to traverse the model surface at an average speed close to 45 km/h. Three-component particle-velocity wave-field histories over this duration were stored by the simulation for later processing. Models of this extent and duration are on the order of the expected range of coverage for battlefield systems such as Raptor or the Future Combat System sensor system. As a consequence, resulting simulation data can be used for system development in a manner similar to field data.

Two types of sources were applied to the geologic model. In the first, the moving vehicle forcing history derives from a pressure signal that was measured in near-surface soil beneath a passing armored tracked vehicle. This measurement—a sequence of pressure pulses—was used to empirically design a moving vehicle force algorithm that varies the pulse frequency in proportion to vehicle speed. Spectrograms of surface particle velocities show that this algorithm, together with the FDTD code, produce ground motion responses not unlike those measured from field experiments with moving tracked vehicles. In the second the forces were calculated using the high-resolution mechanical model DADS (Dynamic Analysis Design System, LMS International, Coralville, Iowa). In particular the model was a 3D dynamic simulation of an M1A1 including suspension dynamics and track-ground interaction. Results from both sources guide our ongoing developments to produce high fidelity tracked vehicle source inputs in order to simulate realistic ground vibration results for sensor system development.

The geological model consisted of two soil layers (above and below a water table) overlying granitic bedrock. Two common geological features distinguish its gently sloping topography: an

outcropping of the bedrock and a trench representative of an eroded streambed. Animations of the particle velocity wave fields reveal the vehicle-induced wave propagation and the geology-induced scattering of the waves. The use of these wave fields for deriving spectral features of moving vehicles, the adaptation of an unattended seismic sensor network to a complex geologic setting, and the application of the geologic adaptations to improve network tracking of tracked vehicles, are demonstrated.

Introduction

The US Army has an interest in the characteristics of seismic surface waves from moving armored vehicles. Using field data Moran and Greenfield (1997) and Prado (1998) have shown that surface waves in mild topographies generally possess high spatial coherence, show smooth amplitude decay as a function of vehicle range, and have little dependence on severe meteorological and seasonal variations. As a consequence these signals are potentially useful to remotely deployed sensor systems that monitor battlefield activities. In support of the Army's seismic sensing needs, we are developing a seismic propagation model that considers the complex effects of topographical features and shallow geological structure on propagating waves. Awareness of these effects can be used to predict system performance and to optimally place sensors.

In this paper we present simulated seismic waves propagating over a topographic surface from a moving tracked vehicle. Two representations of tracked vehicle force inputs are considered. Each moves across the surface of a geologic model that features a large weathered outcrop of bedrock, two soil layers above the bedrock, and an eroded streambed. Specifically we describe the computation, the geologic model, the representations of the moving vehicle, the resulting particle velocity wave fields, and example applications of the data including geologic adaptation and vehicle tracking performance of an unattended seismic sensor network.

Computational Approach and Requirements for the Long-Duration Simulation

Our requirement to simulate seismic wave propagation in the presence of realistic geologic and topographic features necessitates the use of 3-D numerical modeling. Our method (Moran et al., 1999) follows Hestholm and Ruud (1998) and Hestholm (1999), who incorporated surface topography with an appropriate stress-free surface boundary condition into a finite-difference time domain (FDTD) viscoelastic wave propagation model featuring 8th-order, staggered-grid, finite-difference operators. To accommodate surface topography, they express geologic models using a curvilinear grid that is transformed into a rectangular computational grid of equal grid spacing. This mapping can be visualized by proportionally stretching the rectangular grid in the vertical direction so that the free surface matches the topographic function.

Finite-difference seismic simulations over the expected range of coverage for battlefield systems such as Raptor or the Future Combat System sensor system require substantial models and computational durations. In short they are very large computations. As a consequence, our simulation approach consists of parallel computations based upon a domain decomposition strategy (Moran et al., 1999). This requires that the computations be performed on multi-processor computers such as those available at DoD High Performance Computing Modernization Program (HPCMP) centers. The simulations described in this paper were

performed using a Cray T3E at the Army High Performance Computing Research Center. The model dimension was roughly 210 m by 286 m by 80 m (deep) with 1.6-m node rectangular-grid spacing. The side and bottom boundaries were set with a 24-cell-thick absorption layer (Cerjan et al., 1985), providing a reduction of at least –25 dB in reflecting wave particle energy. The simulated durations were up to 24 s with time steps of 180 μs. This period reflects the time required for a tracked vehicle to traverse the model surface at speeds varying between 35 and 55 km/h. Three-component particle-velocity wave-field histories over this duration were stored by the simulation for later processing. The simulation ran for nine hours.

Force inputs to our models must be able to accurately represent the complex mechanical loads generated by tracked vehicles operating over varying topographical surfaces. This objective requires us to focus on the absolute magnitudes of particle velocities resulting from specific force distributions and transients. In previous simulations, by comparison with analytical calculations, we have demonstrated the accuracy of our technique of force input and the resulting propagation in topographic models with highly distorted grid space (Ketcham et al., 2000). We have also demonstrated the accuracy of guided waves in flat-layered models by comparison with wavenumber integration model results and the effects of topography on these waves. We continue with efforts to verify the accuracy of the FDTD simulation technique, which include further comparisons with independent analyses as well as comparisons with measured field experiment data.

Geologic Model

The geologic model is a synthetic model consisting of two fairly stiff soil layers (above and below a water table) overlying granitic bedrock. Two common geological features distinguish its gently sloping topography: an outcropping of the bedrock and a trench representative of an eroded streambed. Figure 1 is a surface contour graph illustrating the topography and these features. Such a setting is typical in glaciated geologic landscapes.

The outcrop is roughly elliptical with dimensions of 80 m by 200 m. Its peak is offset laterally from the center of the streambed by ~150 m. The streambed is roughly 100 m wide by 8 m deep. "Downhill" on the model is from North to South, i.e., from the top of Figure 1 to the bottom, as a gentle 0.002 slope occurs over the model in this direction. The streambed also follows this slope.

Figure 2 illustrates the subsurface layering of the model; it is a slice at the 130-m South-North coordinate. The shades of the model refer to different materials. The upper two layers away from the outcrop are the soil layers. The surface soil layer is approximately 10 m thick. The lower soil layer—i.e., the soil beneath the "water table"—is approximately 15 m thick. The actual values vary throughout the model, as the surface is not flat. In addition, both soil layers reduce in thickness adjacent to the outcrop due to the increasing elevation of the bedrock surface as it rises toward the outcrop, and the upper soil layer thins toward the streambed.

The outcrop features an upper weathered zone. This zone is depicted in Figure 2 by the shading changes in one-cell-thick layers beneath the outcrop. The uppermost nodes in this zone have seismic propagation properties identical to the surface soil layer. The properties vary linearly in eight steps until the granitic layer properties are reached.

Table 1 lists the seismic properties of the three principal layers. The three elastic properties (compression-wave speed, shear-wave speed, and density) are supplemented by two properties required for the viscoelastic modeling of seismic wave attenuation caused by material losses. These are the quality factors Q_p and Q_s, which respectively quantify the phase lags of compressive and shear strains behind the stresses of propagating waves. As Q relates inversely to attenuation, higher attenuation is given by lower quality factors.

Q_p and Q_s were introduced into the model using three viscoelastic mechanisms—at 10, 100, and 1000 Hz—using the technique presented by Xu and McMechan (1998) to approximate constant Q with frequency. This implementation of material damping in our simulation models, while computationally expensive, will ensure that simulated sensor performance tests and algorithm development will have realistic physical bases.

Moving Vehicle Forces and Loading Paths

Two types of moving tracked vehicle sources were applied to the geologic model, an idealized representation of the applied ground forces, and a set of forces based upon a rigorous dynamic model of an M1A1. These are described here.

Idealized Tracked Vehicle Forces

The force history applied in the simulation of the idealized vehicle derives from a force signal that was measured in near-surface soil beneath a passing armored tracked vehicle. This measurement—a sequence of force pulses—was used to empirically design a moving vehicle force algorithm that varies the pulse duration inversely proportional to vehicle speed. Figure 3 illustrates the setup and the idealized result of the measurement. The load cell was located a few centimeters beneath one track of the vehicle while it traversed an unpaved soil layer. The figure depicts a strip-chart-recorder-like trace with wheel-load-generated pulses. The period of the peaks relates to the vehicle speed and wheel spacing as indicated. For this analysis the wheel spacing was set to 1 m, and the maximum force (under the sixth wheel) was set to 100 kN.

The loads were applied as a sequence of vertical point forces over the model surface according to a chosen path and two defined relationships: distance vs. time and speed vs. time. Figure 4 illustrates the path in part (a). At the appropriate starting time for a given point force in the sequence, the algorithm positions the force on the curved path at the location defined by the path and the total distance traversed. The algorithm finds the nearest finite-difference grid point, and the Figure 3b time series is assigned to load this grid point with the illustrated ? t of this series determined by the current vehicle speed.

Dynamic Model of M1A1

The idealized force sequence of Figure 3b and its application have been developed as precursors to rigorous tracked-vehicle ground force models that are currently being formulated within our project. While the idealized force sequence emphasized a moving impulsive load *capability*, the current effort focuses on high fidelity modeling of tracked vehicle ground loading. This work involves defining the distributed vehicle forces at the track-soil interface in great detail using the 3-D high-resolution mechanical model DADS (Dynamic Analysis Design System, LMS

International, Coralville, Iowa), which is a commercially-available mechanical tracked vehicle/suspension dynamics model.

Lacombe et al. (2000) present this technique. A customized utility with graphical user interface (GUI) has been created by LMS personnel to streamline construction of the DADS representation of a tracked vehicle. The GUI emphasizes details within the track and suspension elements, while treating sprung mass elements, such as the hull and turret, as rigid bodies. Suspension layout information is specified in the GUI, as are dimensional, inertial, stiffness and damping properties of common suspension elements (road wheel, road arm, idler, sprocket, support roller and track block). Four different track block configurations can be accommodated, and the initial position of each track block is determined automatically. Interactions between each track block and the ground are represented by multiple point-ground contact elements, whose normal and tangential ground forces are calculated using a modified set of Bekker (1969) constitutive soil equations. A sample output of these forces, which are the forces that are input to our seismic propagation software, is presented in Figure 5.

For the results presented here a DADS model of an M1A1 tank was built and driven in a simulation over the terrain illustrated in Figure 1. This was performed on a Silicon Graphics Onyx2 at the Tank-Automotive Research, Development & Engineering Center. At the time of this writing only a partial result was available—the 14-s ground forcing path shown in Figure 4b. Seismic propagation results from this 14-s path, presented subsequently, are the initial results from this effort.

<div align="center">

Particle Velocity Wave Fields

</div>

Figures 6 and 7 depict propagation model results from the force inputs of the idealized tracked vehicle. These include images of the vertical particle velocity, w, illustrating the ground vibration on the model surface, and w vs. time over the duration of simulation from "receiver" locations. Similar results from the propagation model of the M1A1 are shown in Figure 8. Each set of results is discussed below.

Results from Idealized Tracked Vehicle Propagation Model

Figures 6a and 7 contain the vertical particle velocity images, or snapshots, of this simulation. These were constructed from the output of the simulation at each finite-difference grid point on the surface, providing a spatial resolution of 1.6 m. A scale in Figure 6a gives the correspondence between the image shade or color and the velocity amplitude in m/s. The center of the scale is 0 m/s. Lower amplitude velocities around 0 m/s are mapped with shades of brown, while higher amplitude velocities, either positive or negative in direction, are accentuated by color. The maximum and minimum values of the scale are set at a small percentage (typically ~2%) of the actual values to optimally reveal the qualitative nature of the propagation.

Particle velocity images of this kind provide a physically intuitive picture of the wave propagation; while these images show velocities rather than displacements, the images are not unlike a snapshot of ripples on water caused by a dropped pebble. Of course the physical nature of the propagation is best seen in animations of the images. Indeed, the Figure 6 and 7 images were taken from an animation of the particle velocity wave field history. This animation shows

the progress of the idealized vehicle along its path by the movement of the concentrated, higher-particle-velocity amplitudes, and reveals the continuous vehicle-induced wave propagation and the geology-induced diffraction and refraction of the waves. The sequence of still images in Figure 7 is discussed here in lieu of the animation.

The principal waveforms displayed in the Figure 7 images are fundamental Rayleigh surface waves, which have cylindrical decay ($1/R^{0.5}$, R=radius) in the absence of the topography and geology that disturb this decay. The propagation illustrated is that from a continuously moving source, as the idealized tracked vehicle forcing time series at a grid point always begins and ends at zero (Figure 3b).

In the initial images of Figure 7 (a-c), the bending of the wave fronts and the apparent variation in wavelength over the surface shows the effect of the shallow bedrock on the propagation between the outcrop and the trench. As indicated in the geology model slice in Figure 2, this area has soil depths that increase toward the trench. Propagation dominated by bedrock causes the longer apparent wavelengths in the South-to-North direction of Figure 7a-c. Conversely, the lower-velocity soil layers produce the shorter wavelengths seen in the West-to-East propagation.

One possible effect of the streambed on the propagation is the bending of the wave fronts evidenced in Figures 7a and 7c. One would expect that the lower, higher-velocity soil layer would impact the propagation direction within the streambed. This appears to be the case, as the wave fronts toward the North end of the trench bend as if they have been accelerated northward by this layer. The Figure 7d-g images show perhaps clearer indications of this directional bias by the longer wave fronts and faster propagation toward both the South and North directions of the streambed.

A further effect of the trench would be to reflect energy of the surface waves, especially if the bottom of the streambed reached the bedrock (Ketcham et al. 2000). The Figure 7a-c snapshots reveal, however, that this phenomenon does not dominate the propagation as the surface wave energy transmits readily to the lower soil layer and the wave fronts pass the trench with their form intact.

The idealized vehicle's speed with time over its path (presented later as part of Figure 9) indicates that any effect of lower speeds on the propagation should be evident in the period from 6 to 17 s. Indeed, Figure 7c-f from the 7, 10, 13, and 16-s snapshots indicate longer wavelengths caused by the lower-frequency pulses. Because of the longer wavelengths, however, there is a greater interaction with the deeper, higher-velocity bedrock layer that distorts the wave fronts. The distortion also results in a higher effective surface wave velocity.

In all images of Figure 7 there are much lower particle velocity amplitudes on the rock outcrop relative to the soil layer surfaces. This is because a stiffer, higher-velocity material will vibrate at lower amplitudes in response to the same amount of propagating energy. The stiffness contrast between the rock outcrop and the soil layers causes energy to reflect, moreover, and this is revealed in the reflection pattern between the outcrop and trench in Figure 7f. Overall the combined effect of the outcrop, trench, and shallow bedrock is to reduce the waveform coherence—i.e., they break up the wave fronts. In general Figure 7 and especially the full

animation displays greater uniformity of the wave fronts in the deeper soil regions and somewhat discontinuous wave fronts in locations between the outcrop and ravine.

Figure 6b presents the vertical particle velocity w vs. time series taken from the full wave field results. These signals, shown over the entire simulation duration, are from the four "receiver" locations depicted in Figure 6a. (West-East, South-North, elevation) coordinates are indicated in Figure 6b. All are on the 106-m South-North coordinate plane.

It can be seen that the signals closest to the vehicle path—i.e., the three easternmost receivers in Figure 6b—show the strongest response when the vehicle is close to the receiver. In contrast, the westernmost receiver on the outcrop does not show such a peaky response, as it is farther from the path. The peak level of response in the outcrop receiver is 1-2 orders of magnitude less than in the eastern receivers, reflecting both the lower amplitude response of the bedrock and outcrop and the remote location of the receiver.

Results from M1A1 Propagation Model

The results presented in Figure 8 (and subsequently in Figure 10) from the propagation model of the M1A1 are our first results from using the ground force outputs from a DADS mechanical model of a tracked vehicle as inputs to our finite difference wave propagation code. They are results that are far more consistent with developing a software capability than with demonstrating or investigating the seismic wave propagation emanating from a moving M1A1. With that stated, however, the results have notable characteristics that are guiding our ongoing developments.

Similar to the set of results presented in Figure 6, Figure 8 contains an image of the vertical particle velocity and w vs. time signals from the M1A1 propagation model. In contrast to the propagation from the idealized tracked vehicle force inputs, Figure 8a shows a wavefield with noticeably shorter wavelength and higher frequency propagation, while Figure 8b shows periods of higher particle velocity that are not due to the vehicle passing close to the receiver location.

The shorter wavelength/higher frequency propagation evident in Figure 8a apparently results from high frequency pulses in the force inputs that are not quickly damped out by material loss in the finite difference calculations or eliminated by the soil model used for the M1A1 DADS simulation. These are subjects that we are currently investigating as they will impact how we perform our mechanical vehicle modeling and select material properties for modeling inputs. The periods of higher particle velocity at approximately 4.5 and 13 s in Figure 8b are due to complex ground forces predicted by the M1A1 mechanical model during turns of the vehicle in the vehicle simulation. An animation of the vehicle driving on its path shows that the high amplitude signals just before time=5 s occur coincidently with a severe turn that results in track blocks sliding tangentially over the surface. What is clear from these features, which contrast with the idealized model results, is that the meaningful seismic propagation simulations require realistic mechanical representations of the tracked vehicles. This becomes practical with high-resolution vehicle-dynamics modeling.

Recognizing (1) that the vertical particle velocity is the quantity that would be recorded in a field measurement by a vertically oriented geophone, and (2) that geophones will be employed in

battlefield seismic sensors, reveals the utility of seismic propagation simulations. Indeed, by providing the full wave field history over the surface of the model, data from simulations can be applied to complement and, in some cases, replace field data in the development and acquisition of systems. Examples of these applications are given in the next section.

Applications

High-fidelity seismic wave propagation simulations such as those described in this paper can be used for system development and system performance prediction. Quantitative descriptions of the seismic wave field over time and space are particularly suited for ground sensor networks since they allow placement of virtual sensors at any point in the simulation domain. Most ground sensor system functions include target detection and system wake-up, target range and bearing estimation, and target classification.

Spectral Features for Classification

Target classification is generally achieved by estimating spectral features in signals. For seismic signals, Moran et al. (1998b) use spectrograms to display these features. Spectrograms are signal frequency content vs. time images that detail the evolving spectral character of the signal with time (Oppenheim and Schafer, 1989; MathWorks, 1998). They are quantified by calculating successive Fourier magnitudes of a signal using a sliding window and are displayed by plotting each spectrum as a shaded image at the time corresponding to the center of its window.

Figure 9 contains a power spectrogram of the w signal from the top-of-outcrop receiver location of the idealized tracked vehicle propagation model, which was shown in Figure 6b. Figure 9 also contains the speed vs. time graph of the vehicle along its path for comparison with the spectral variations. The shaded scale in Figures 9b gives the association between the image shade and the power of w relative to 1 $(m/s)^2/Hz$, in decibels. The darker orange shades show the frequency content with the highest powers—i.e., the signal spectral content—while the lighter and blue shades show the spectral regions with relatively little signal power.

The principal signature features of the Figure 9 spectrogram are the multiple harmonic lines at any given time and the clear relationship between the changing spectra and the vehicle speed. These features are like those measured from field experiments with moving tracked vehicles (Moran et al., 1998b).

Similar graphs are shown in Figure 10 for results of the M1A1 propagation model. Here the spectrogram signal is from the receiver location between the outcrop and trench (Figure 8a). Figure 10 also includes the w vs. time signal from this location for direct comparison with the spectrogram. Again the greater complexity of the propagating energy from the M1A1 simulated forces relative to the propagating energy from the idealized tracked vehicle is evident. The spectrogram nonetheless contains clear spectral lines and their harmonics that depend on the vehicle speed, especially in the periods 0–5 s and 8–13 s. Just before the 5-s time the energy due to the turning of the M1A1 dominates the spectral content. However, this energy occurs with the same harmonics as the speed-dependent spectral lines. These are realistic features. They are indications that our modeling developments are providing us with physically correct simulations.

Adapting to Geology—Network Tracking using Bearing and Range Estimates

A simulated network of seismic sensors can allow algorithm development for tracking vehicles over a battlespace. As an example, Figure 11 gives a map of a simulated unattended seismic sensor network on the terrain of the propagation models described previously (Figure 1). Fourteen sensor nodes make up the network. Each node contains four vertical seismic sensors (virtual geophones) within a 3-m aperture.

As an exercise of how an algorithm can adapt this network to the geology to improve tracking performance, a propagation model was conducted simulating a sequence of four calibration pulses that are set off in or dropped onto the sensor field from, say, a helicopter. Locations of the simulated calibration pulses are indicated by asterisks in Figure 11. They were meant to represent a fly-over path along a likely target vehicle path.

Figure 12 shows four snapshots of this simulation. Each depicts a vertical particle velocity image over the surface just after the calibration pulses are initiated at 0, 0.5, 1, and 1.5 s. Corresponding raw data signals from all 56 sensors of the network are shown in Figure 13. It is from these ground vibration responses to the pulses and from knowing the location of the calibration sources that the network tracking algorithm was able to learn how to adapt to this particular geologic setting. The correction technique is illustrated in Figures 14 and 15. Figure 14 a and b show bearing and range correction polynomials as a function of the observed bearing and range, respectively. By evaluating these polynomials the algorithm was able to roughly correct for curving ray-paths in lines of bearing and to estimate passive ranging coefficients for each node in the network. As examples, Figure 15 a and b depict results of the corrections for line-of-bearing at node 8 and range at node 3, respectively. In each the red line is the true bearing or range from the node to the calibration pulse, the blue circle is the estimated bearing or range based on raw data, and the green circle is the corrected bearing or range based on geologic adaptation. It is apparent that the corrections are not perfect and can deviate considerably from true. The tracking result in Figure 16, however, reveals that individual deviations are overcome by the redundancy of the network.

Figure 16 shows the estimated track relative to the actual track of the idealized vehicle, originally shown in Figure 4a. The estimate track was based upon the line-of-bearing and range calculations with geologic adaptation, using the vertical particle velocity data from the idealized tracked vehicle propagation model presented previously. An inversion was performed using a minimization technique that simultaneously accounted for bearing and range, and the best-fit path shown in Figure 16 was produced.

While the Figure 16 result indicates that seismic network tracking using geologic adaptations is very promising, this again is a very preliminary result. Further development and complete testing of these techniques is scheduled, and subsequent presentations will detail our results. It is clear, however, that by using simulated wave propagation data we have demonstrated:

- high population, unattended ground sensor network (UGS) tracking performance,
- a fully realizable "self adapting" UGS network,

- that a complex geologic condition can be overcome by an adaptable seismic tracking network, and
- a cost effective procedure, particularly compared to large scale field trials, for developing seismic network tracking algorithms.

Conclusion

The moving vehicle seismic wave propagation simulations we have performed in the past year using DOD High Performance Computing Resources are the first such simulations produced by a seismic model. The synthetic wave field particle velocity images reveal realistic and expected seismic propagation physics. Furthermore, the simulated tracked vehicle signatures contain principal features of seismic vehicle signatures observed in field measurements of moving tracked vehicles. These results reveal the capability of the simulation model and vehicle force algorithms employed.

Our example applications demonstrate the utility of the simulations for system development and user situational awareness. Specifically, the ability to test how an unattended ground sensor network can adapt to local geology, and the application of the adaptations to improve tracking performance, were demonstrated. The algorithms employed, while preliminary, are promising techniques for UGS networks.

More generally these results provide a strong indication that high performance computational simulations have a role in seismic system development and acquisition. Their impact can be seen as reducing system costs and development time, improving system performance in complex environments, and allowing propagation physics to be incorporated into system algorithms.

Acknowledgments

References

Bekker, M.G., 1969, *Introduction to Terrain-Vehicle Systems*, University of Michigan Press, Ann Arbor, MI.

Cerjan, C., Kosloff, R., and Reshef, M., 1985, A Nonreflecting Boundary Condition for Discrete Acoustic-Wave and Elastic-Wave Equations, *Geophysics*, V. 50, pp. 705–708.

Hestholm S., and Ruud, B., 1998, 3-D Finite-Difference Elastic Wave Modeling Including Surface Topography, *Geophysics*, V. 63, pp. 613–622.

Hestholm, 1999, Three-Dimensional Finite-Difference Viscoelastic Wave Modeling Including Surface Topography, *Geophysics Journal International*, V. 139, pp. 852-878.

Ketcham, S., Moran, M., and Greenfield, R., 2000, The Effect of a Topographic Depression on Guided Seismic Surface Waves, Expanded Abstracts With Biographies, 2000 Technical Program, Volume II, Proceedings of the SEG International Exposition and Seventieth Annual Meeting, Society of Exploration Geophysicists, Tulsa, OK, ST 1.6, pp. 2213-2216.

Lacombe, J., Moran, M., and Happel, S., 2001, A 3-Dimensional Dynamics Model for Generation of Tracked Vehicle Seismic Signals, Proceedings of the 2000 Meeting of the MSS Specialty Group on Battlefield Acoustic and Seismic Sensing, Report 440000-195-X(I), ERIM International, Inc., Ann Arbor, MI, pp. 377-383.

MathWorks, Inc., 1998, *Signal Processing Toolbox User's Guide*, Version 4, The MathWorks, Inc. Natick, MA.

Moran, M., and Greenfield, R., 1997, Seismic Detection of Military Operations, 97-CEP-511-1, U.S. Army Maneuver Support Battle Laboratory, Ft. Leonard Wood, MO.

Moran, M., Boulanger, P., Greenfield, R., Gilligan, T., 1998a, Range Estimation with Seismic Sensors for Early Detection, Final report 98-CEP-0505, Maneuver Support Battle Lab, U.S. Army Engineer School, Ft. Leonard Wood, MO.

Moran, M., Greenfield, R., Prado, G., Turpening, R., Peck, L., Kadtke, J., Carnes, B., Bass, H., Detsch, R., Hawley, B., and Ketcham, S., 1998b, Seismic Feasibility Study in Support of Hornet, Final report of PM-MCD Seismic Eagle Team, U.S. Army ARDEC, AMSTA-DSA-MCD, Picatinny Arsenal, NJ.

Moran, M., Ketcham, S., and Greenfield, R., 1999, Three Dimensional Finite-Difference Seismic Signal Propagation, Proceedings of the 1999 Meeting of the MSS Specialty Group on Battlefield Acoustic and Seismic Sensing, Report 440000-147-X, ERIM International, Inc., Ann Arbor, MI, pp. 1-12.

Oppenheim, A., and Schafer, R., 1989, *Discrete-Time Signal Processing*, Prentice-Hall, Englewood Cliffs, NJ.

Prado, G., 1998, Presentation Materials and Personal Communications, Boston, MA, SenTech, Inc.

Xu, and McMechan, , 1998, Efficient 3-D Modeling with Application to Near-Surface Land Seismic Data, *Geophysics*, V. 63, pp. 601-612.

Figure Captions

Figure 1. Surface contour graph of geologic model illustrating weathered bedrock outcrop, eroded streamed, and gently sloping flats. Contour values are given in meters above an arbitrary datum.

Figure 2. Slice through model at South-North coordinate = 130 m. Distinct shades in graph illustrate layering, with principal layers being granitic bedrock and soil below and above water table. Shading variations in bedrock outcrop are property variations to imposed "weathering."

Figure 3. (a) Six-axle tracked vehicle and (b) idealization of force vs. time record from a six-axle tracked vehicle.

Figure 4. Paths of ground force inputs over topographic surface in propagation models. (a) Idealized tracked vehicle and (b) M1A1 model.

Figure 5. (a) Generic tracked vehicle in DADS, and (b) sample normal and tangential force vs. time output at ground/track block interface.

Figure 6. Idealized tracked vehicle propagation model results. (a) Image of vertical particle velocity w over topographic surface from vehicle forces at time = 17.6 s, and (b) w vs. time over the duration of simulation from the four "receiver" locations denoted by the red triangles in (a).

Figure 7. Idealized tracked vehicle propagation model results. Images of vertical particle velocity w over surface from vehicle forces at simulation times (a) 1 s, (b) 4 s, (c) 7 s, (d) 10 s, (e) 13 s, (f) 16 s, (g) 19, and (h) 22 s. See Figure 6a for velocity scale.

Figure 8. M1A1 propagation model results. (a) Image of vertical particle velocity w over topographic surface from forces of high-fidelity model at time = 5.7 s, and (b) w vs. time over the duration of simulation from the four "receiver" locations denoted by the red triangles in (a).

Figure 9. Idealized tracked vehicle propagation model results. (a) Speed vs. time of idealized vehicle in comparison to (b) spectrogram of w signal at top-of-outcrop receiver location (50, 106, 85) m.

Figure 10. M1A1 propagation model results. (a) Speed vs. time of idealized vehicle in comparison to (b) w vs. time signal at receiver location (150, 106, 78) m and (c) corresponding spectrogram.

Figure 11. Simulated network of seismic sensors. 14 sensor nodes made up the network, with each node having four vertical particle velocity sensors (i.e., virtual geophones) in a 3-m aperture. Locations of simulated calibration pulses for geologic adaptation are indicated by asterisks.

Figure 12. Images of vertical particle velocity w over surface from simulated calibrated pulses just after pulses were initiated at approximately 0, 0.5, 1, and 1.5 s, respectively, for (a)–(d).

Figure 13. Simulated raw data from calibrated pulses collected by network seismic sensors. The pulses occurred at approximately 0, 0.5, 1, and 1.5 s. Each of the 14 nodes had four sensors; thus there were 56 total channels of data.

Figure 14. Network correction functions for (a) line-of-bearing and (b) range bias errors. Each curve represents a correction polynomial for a specific node of the network.

Figure 15. Example network corrections to calibration pulse locations. (a) Corrected line-of-bearing for node 8 and (b) corrected range for node 3.

Figure 16. Estimated track (brown) relative to actual track (red) of idealized vehicle based upon line-of-bearing and range calculations with geologic adaptation.

Table

Table 1. Seismic properties of layer materials in geologic model.

Layer	Compression-wave speed (m/s)	Shear-wave speed (m/s)	Density (kg/m^3)	Material loss quality factors Q_p, Q_s
Upper soil	1000	577	1750	20, 10
Lower soil	1600	625	2000	30, 15
Granitic bedrock	3500	2333	2650	75, 36